

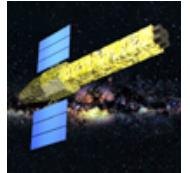
Development of Semiconductor Compton Telescope

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October 18, 2005
LLNL Seminar
Livermore, CA



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RIKEN

J. Kataoka

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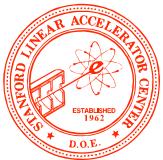
M. Nomachi

Osaka University

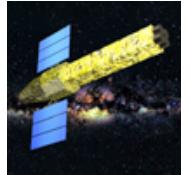
M. Tashiro

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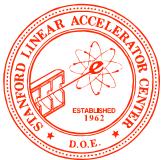
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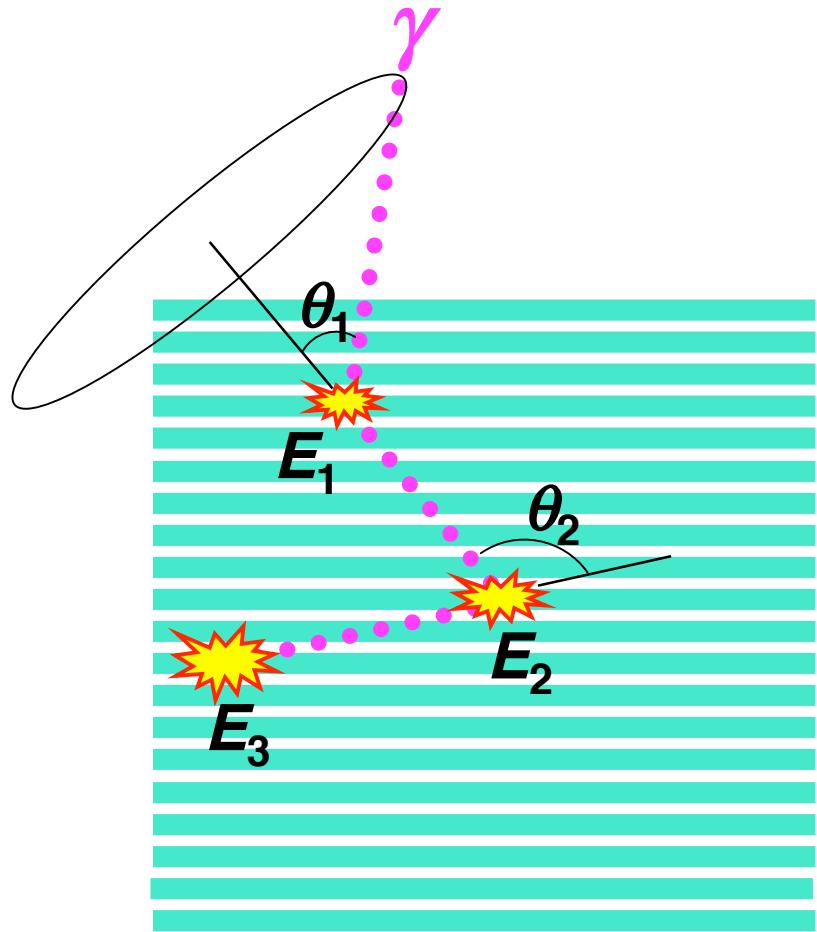
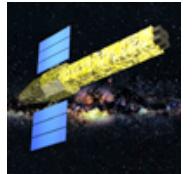
Outline



- **Instrument concept.**
- **Expected Performance.**
- **Technology Development.**
- **Experimental results.**
 - Energy resolution.
 - Compton Reconstruction.
- **Future Prospects.**



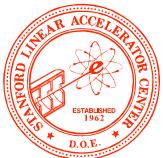
Compton Detector Concept



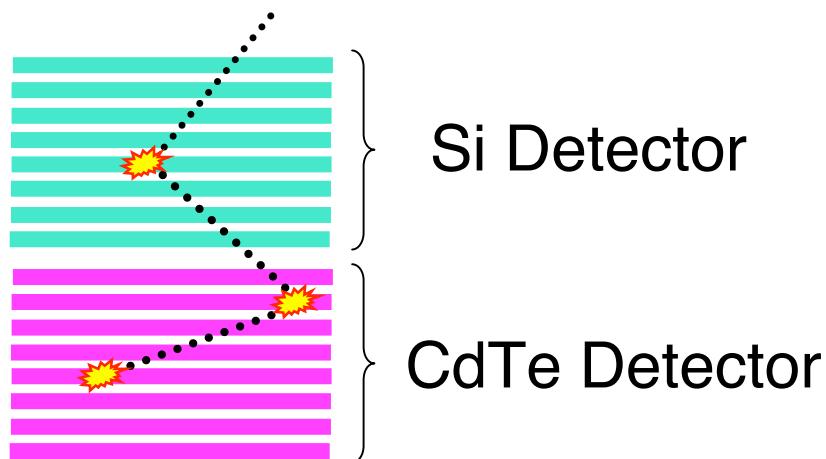
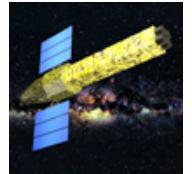
$$\cos\theta_1 = 1 + \frac{m_e c^2}{E_1 + E_2 + E_3} - \frac{m_e c^2}{E_2 + E_3}$$

$$\cos\theta_2 = 1 + \frac{m_e c^2}{E_2 + E_3} - \frac{m_e c^2}{E_3}$$

Proposed by T. Kamae *et al.* 1987

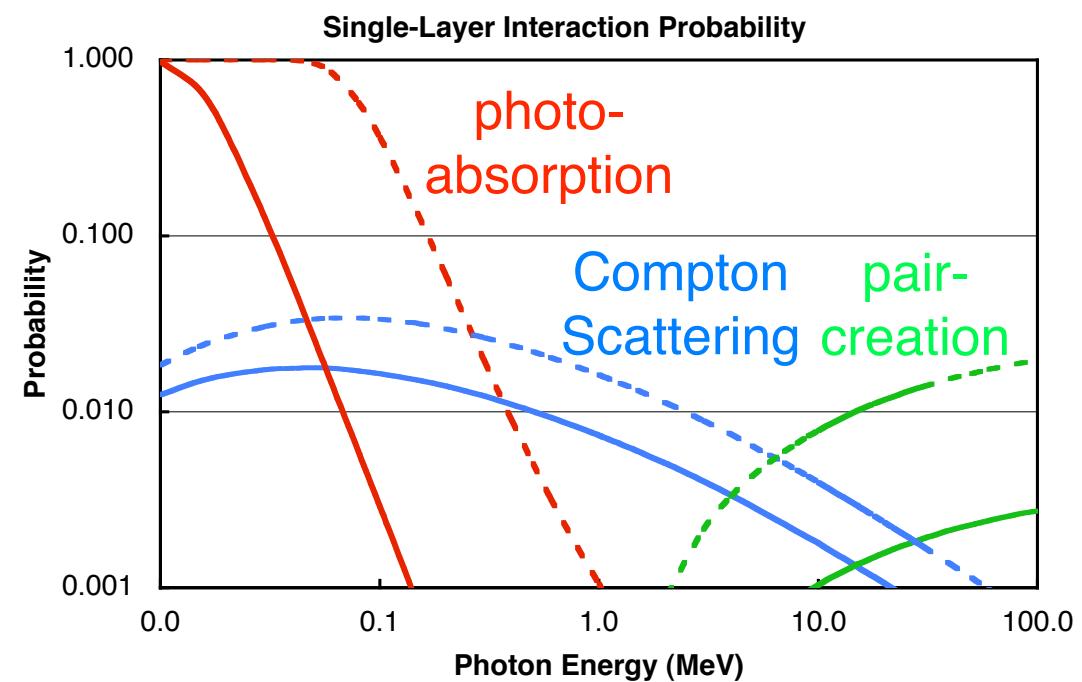


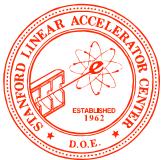
Semiconductor Compton Telescope



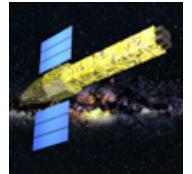
— Si
..... CdTe

Doppler broadening is much smaller in Si.

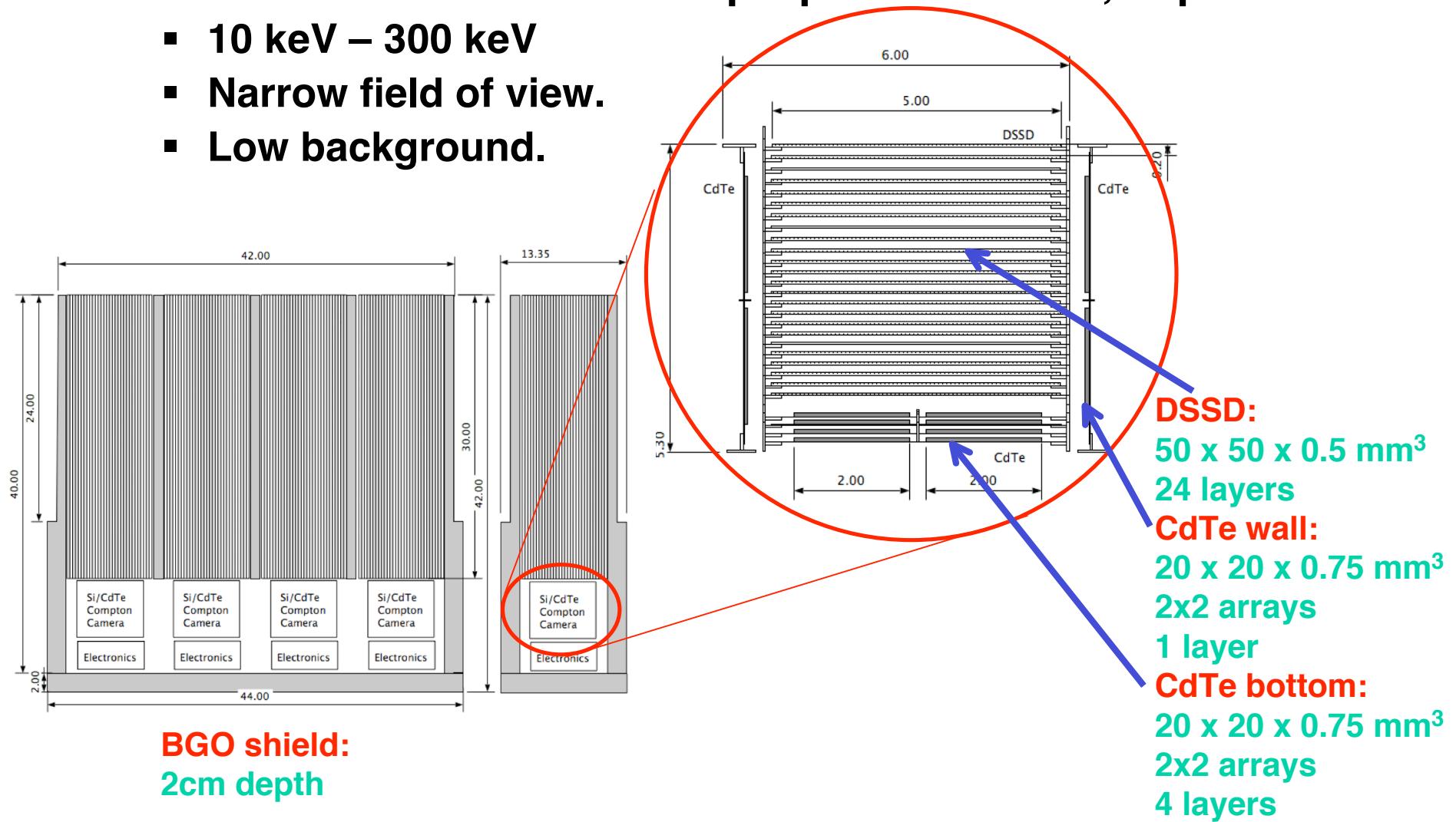




Soft Gamma-ray Detector

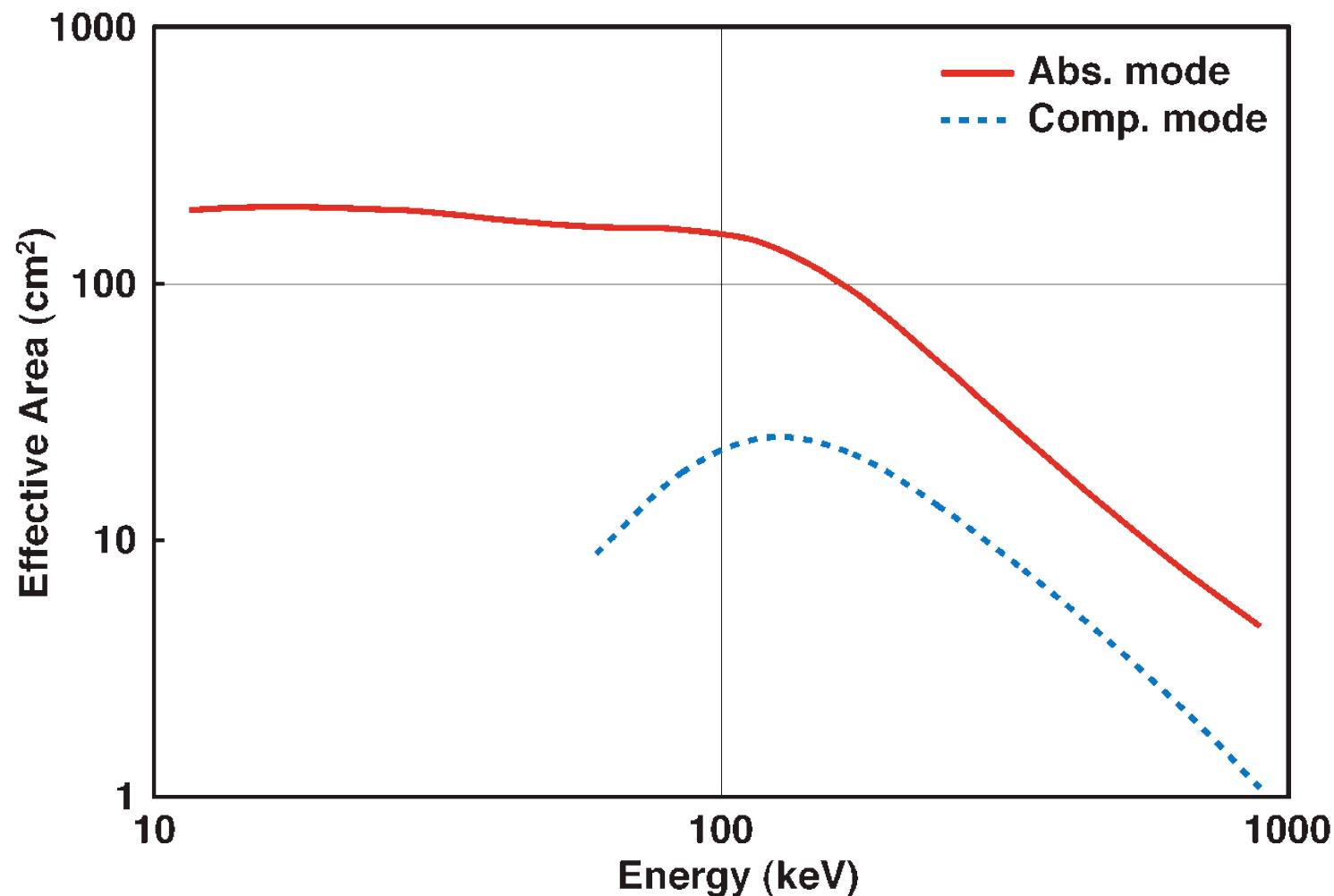
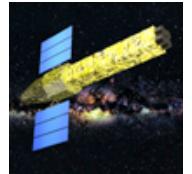


- SGD aboard NeXT mission proposed at ISAS, Japan.
 - 10 keV – 300 keV
 - Narrow field of view.
 - Low background.





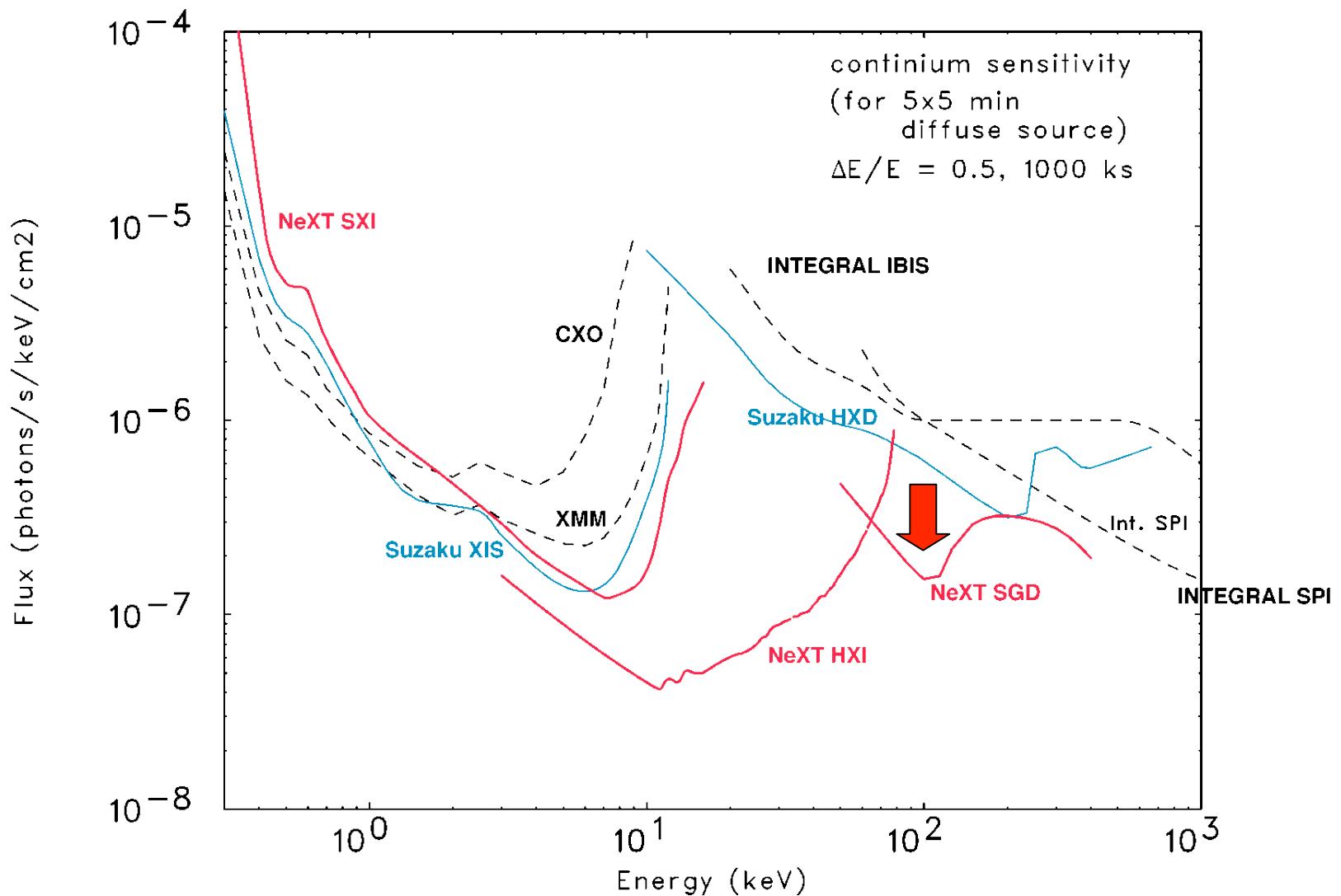
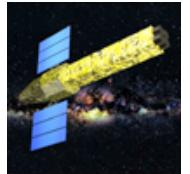
SGD Effective Area



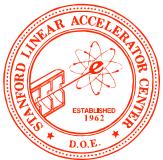
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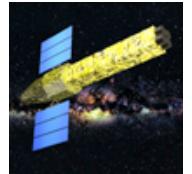
SGD Photon Sensitivity



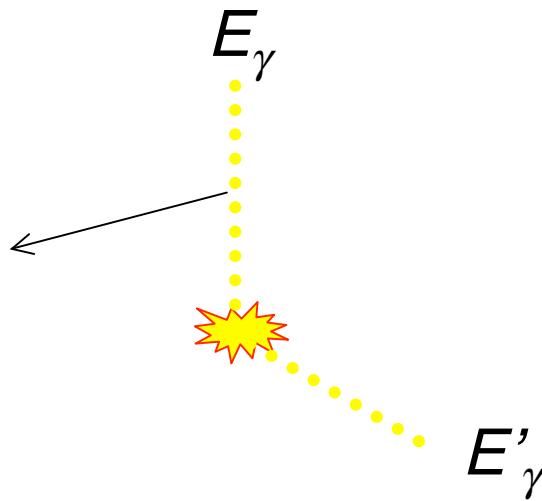
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SGD Polarization Sensitivity

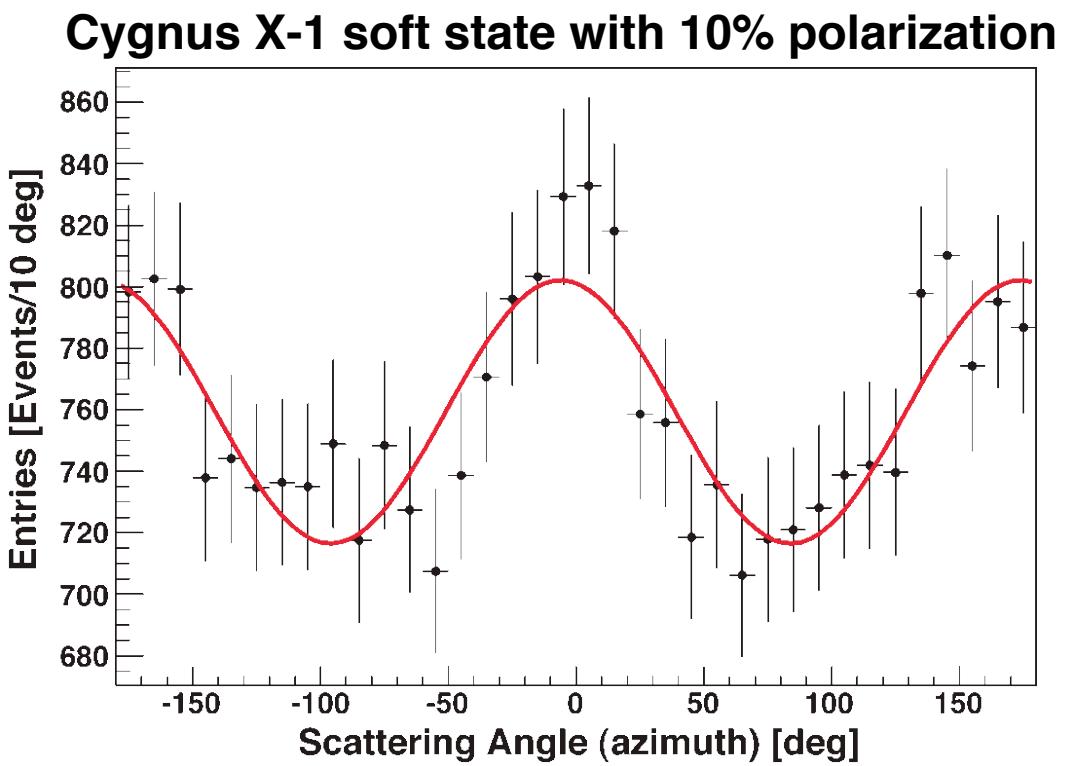


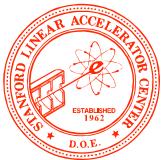
$$\frac{\partial\sigma}{\partial\Omega} \propto \left(\frac{E'_\gamma}{E_\gamma}\right)^2 \left(\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2 \sin^2 \theta \cdot \cos^2 \phi \right)$$



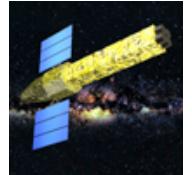
$$AVG \cdot (1 + Q \cdot \sin 2(\phi - \chi_0))$$

5 σ detection limit:
5.4% for Cygnus X-1 soft state
2.4% for Cygnus X-1 hard state
100 ks observation

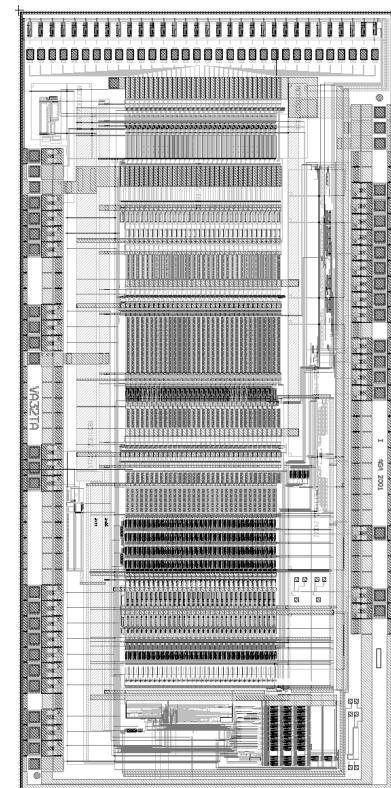




Technology Development

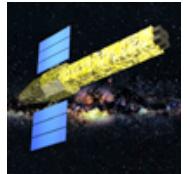


- **Key R&D issues**
 - **Low noise electronics: collaboration with Ideas, Norway.**
 - Crucial for BG rejection by Compton kinematics:
~1 keV(FWHM) (~120 electrons rms)
 - VA32TA, VA32TALP, VA64TA1
 - Low power (0.2mW/channel)
 - **CdTe detector technologies.**
 - High quality CdTe detector
 - Bump bonding
 - **Compact packaging.**

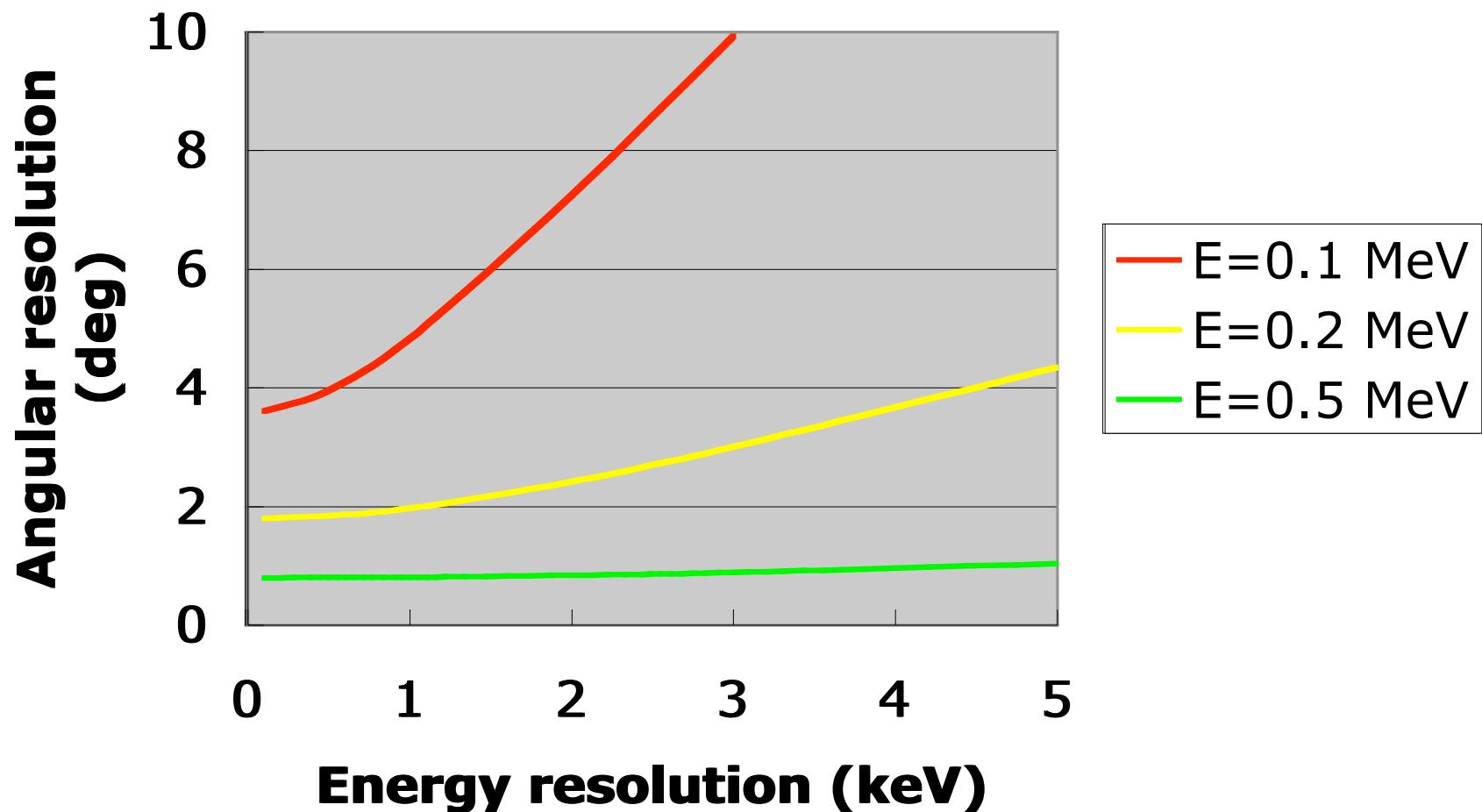




Angular Resolution

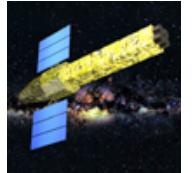


Doppler broadening will limit ultimate angular resolution.

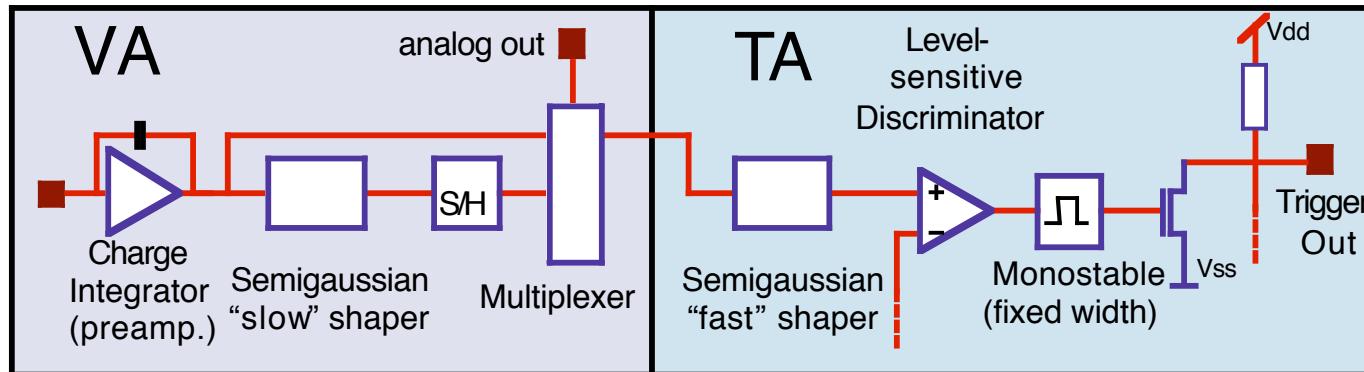




VATA: Low Noise Front-end ASIC



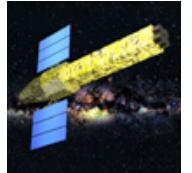
- **Low noise and low power consumption**
 - Front-end MOSFET geometry optimized for small capacitance.
 - VA32TA: 2 mW/channel, shaping time $2 \mu\text{s}$ $(45 + 19 \times C)/\sqrt{\tau} [e^-]$ (RMS)
 - VA32TALP: 0.2 mW/channel, shaping time $4\mu\text{s}$, $108 e^-$ @ 6 pF .
 - VA64TA1: 0.2 mW/channel, shaping time $4\mu\text{s}$ $(76 + 24 \times C)/\sqrt{\tau} [e^-]$ (RMS)
- **Fast shaper for trigger. (75–600 ns)**



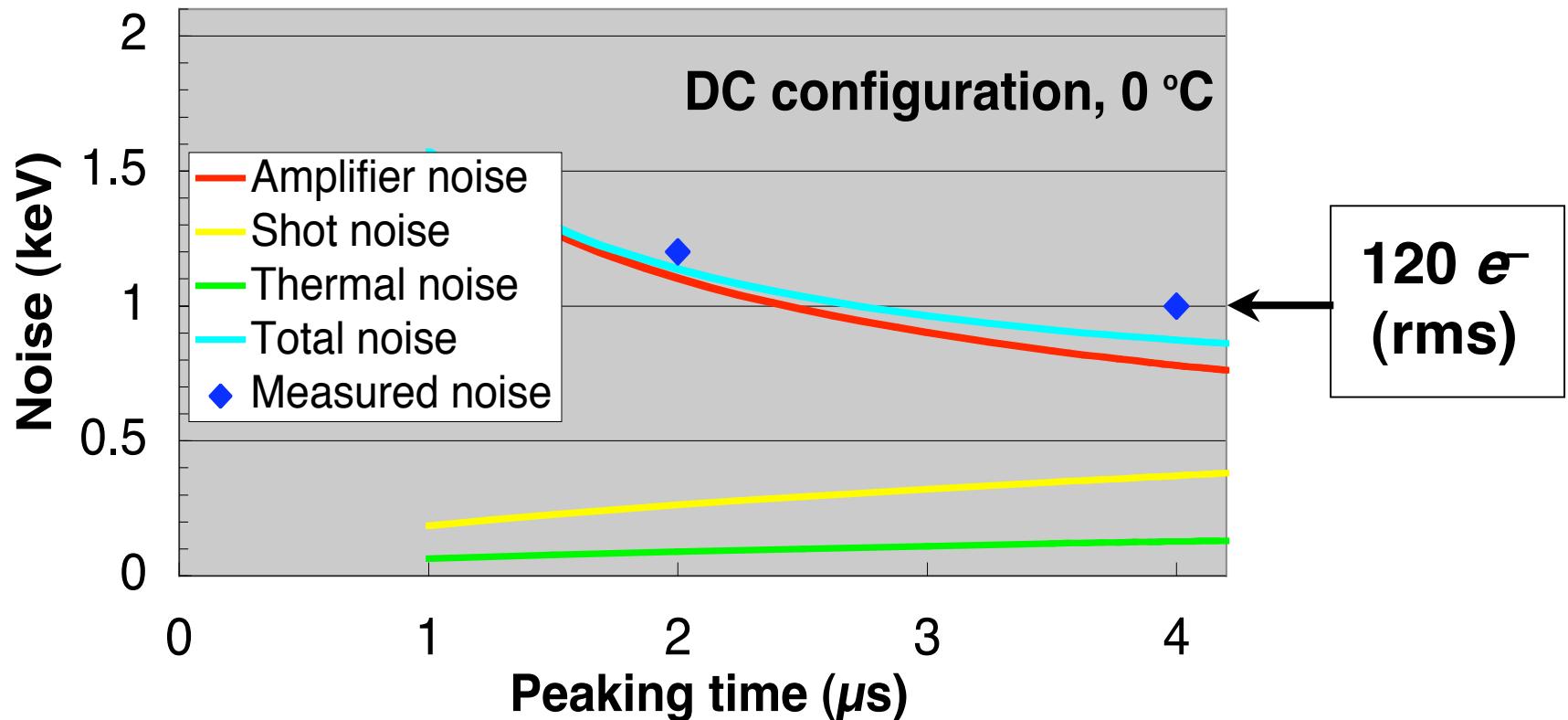
- **Internal DAC (4-bit trim DAC, bias).**
- **Radiation hard to 20 MRad.**
- **SEU (single event upset) tolerant. ($>70 \text{ MeV}/\mu\text{m}^2$)**
- **Integrated ADC and common mode noise reduction in development.**



Noise Analysis

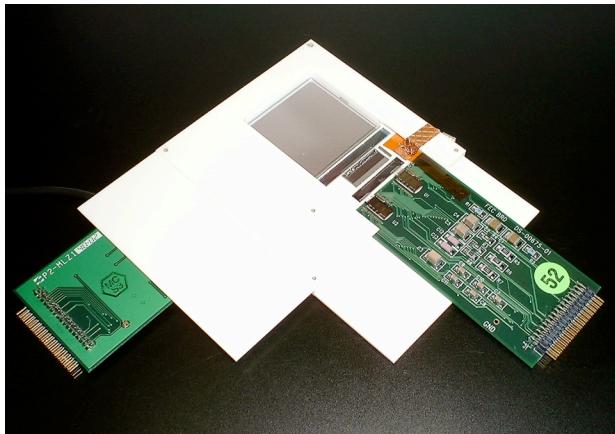
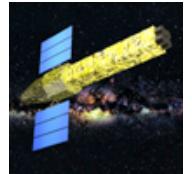


- **Amplifier noise:** capacitance load.
- **Shot noise:** leakage current.
- **Thermal noise:** detector bias resistance.





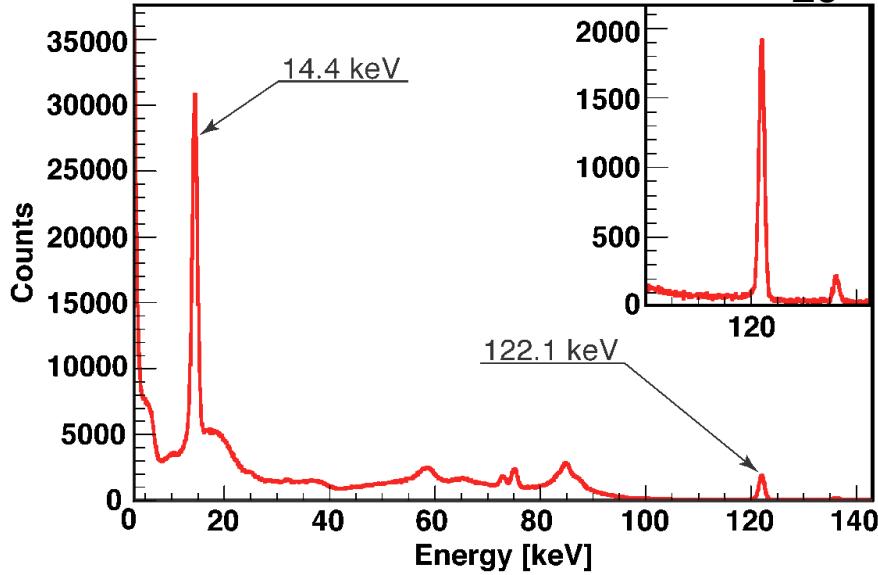
DSSD Energy Resolution



DSSD
2.56x2.56 cm²
0.4 mm pitch
0.3 mm thick

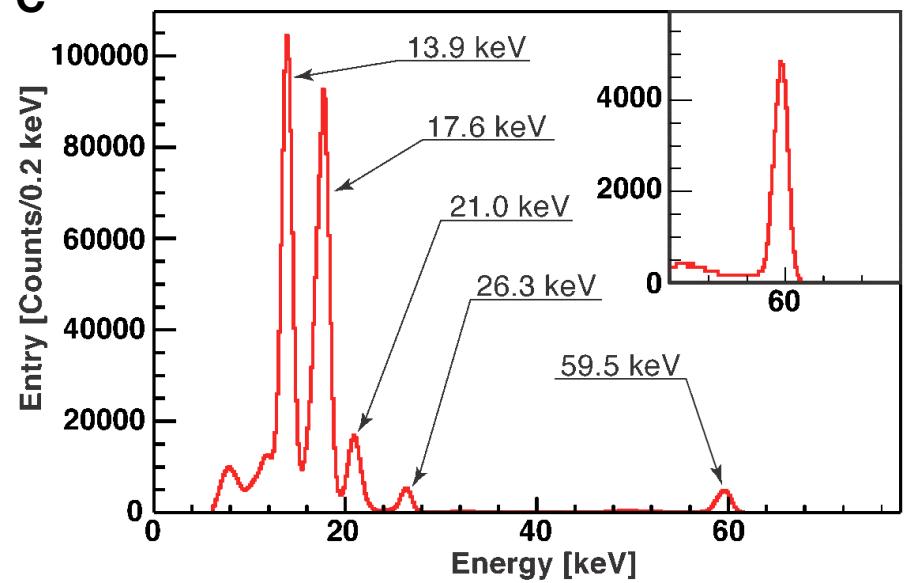
Energy	Resolution (FWHM)
13.9 keV	1.1 keV
14.4 keV	1.1 keV
60 keV	1.3 keV
122 keV	1.3 keV

Fukazawa, et al. SPIE 2004



Operation temperature
-20 ~ 0 °C

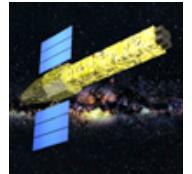
H. Tajima, et al. SPIE 2002



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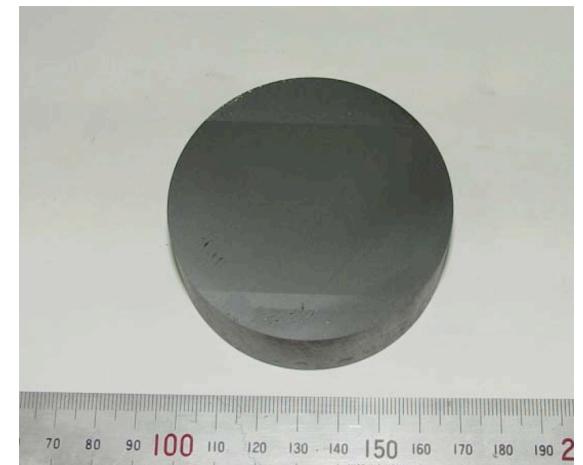
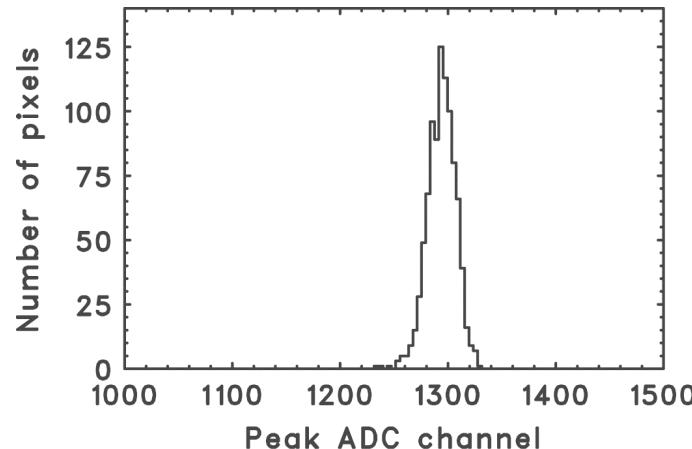


CdTe Detector Development



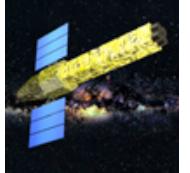
- **THM(Traveling Heater Method)-CdTe by ACRORAD.**
 - Single crystal 7 cm ϕ CdTe.
 - Highly uniform detector performance.

K. Oonuki, et al.
SPIE 2004



ACRORAD

- **Biggest challenge for CdTe/CZT: poor mean drift path.**
 - Electron: $\mu\tau E = 3 \times 10^{-3} \text{ cm}^2/\text{V}$
 - Hole: $3 \times 10^{-4} \text{ cm}^2/\text{V}$ (THM-CdTe), $0.5 \times 10^{-4} \text{ cm}^2/\text{V}$ (HPB-CZT)
 - Much smaller than Si: 0.42 (e), 0.22 (h) cm^2/V .
 - Require high bias voltage for better charge collection.

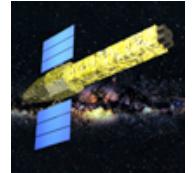


Reducing Leakage Current

- **Higher bias voltage can be enabled by lower leak current.**
 - **Cooling the detector.**
 - 10 pA @ 100V, -20°C for $0.5 \times 0.5 \times 0.5 \text{ mm}^3$
 - **In/CdTe/Pt Schottky diode.**
 - Hole collection via Pt cathode.
 - Root temperature operation.
 - 800 pA @ 500V, 20°C for $2 \times 2 \times 0.5 \text{ mm}^3$
 - Guard-ring to remove leak current from peripheral.
 - 20 pA @ 500V, 20°C for $2 \times 2 \times 0.5 \text{ mm}^3$

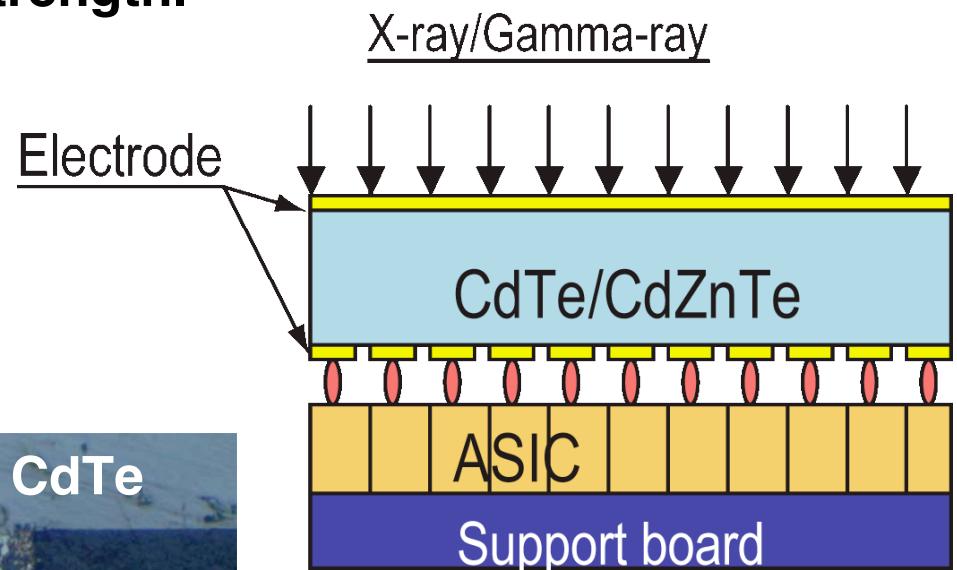
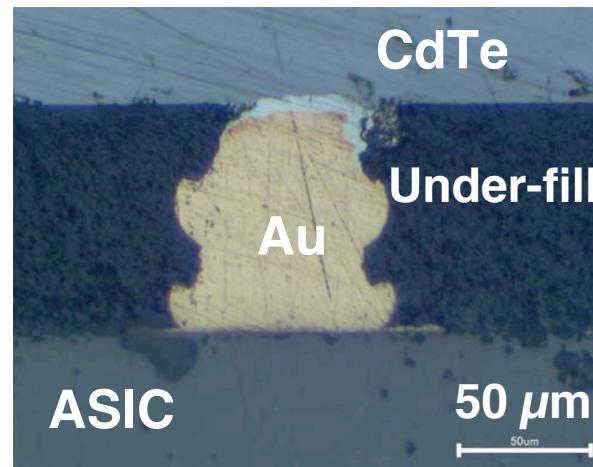
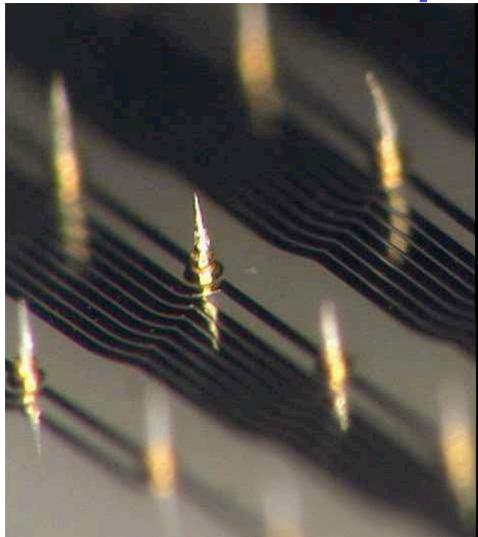


Bump Bonding Technology for CdTe



- In/Au stud bump bonding technology
 - Soft enough for CdTe/CZT.
 - Under-fill for mechanical strength.

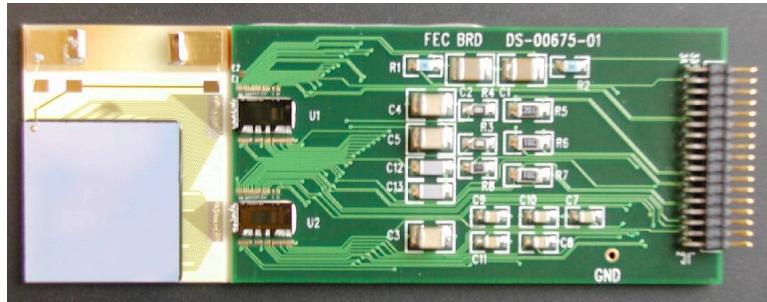
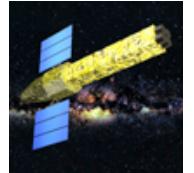
In/Au Stud bump



T. Takahashi, et al.
IEEE TNS 2001

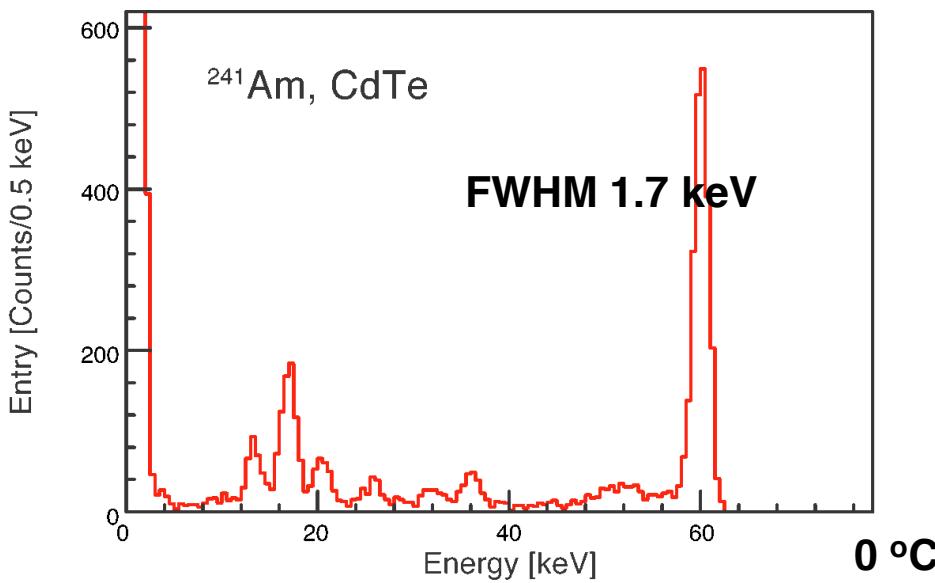


CdTe Energy Resolution

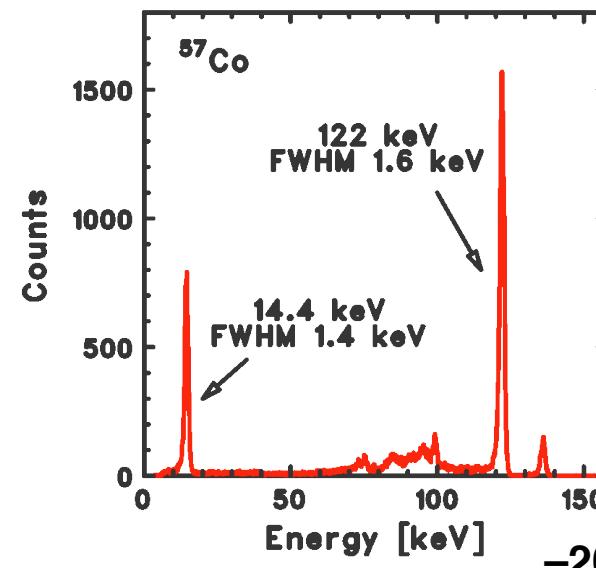
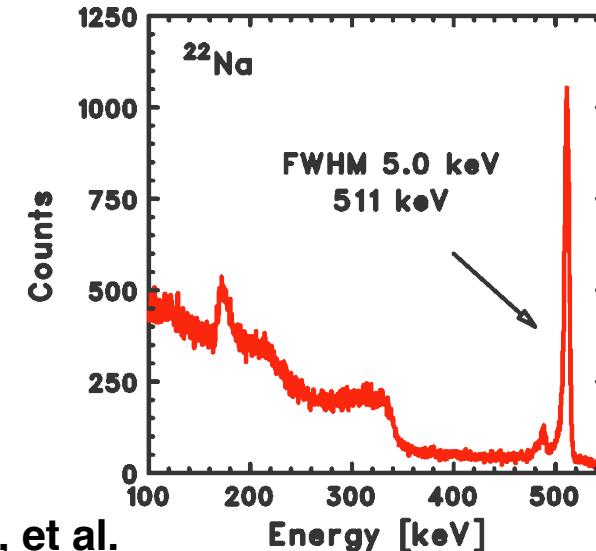


**CdTe pixel
1.6x1.6 cm²
2x2 mm² pixel
0.5 mm thick**

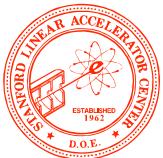
T. Mitani, et al. IEEE TNS 2004



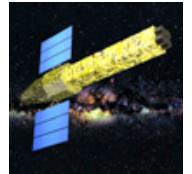
K. Oonuki, et al.
SPIE 2005



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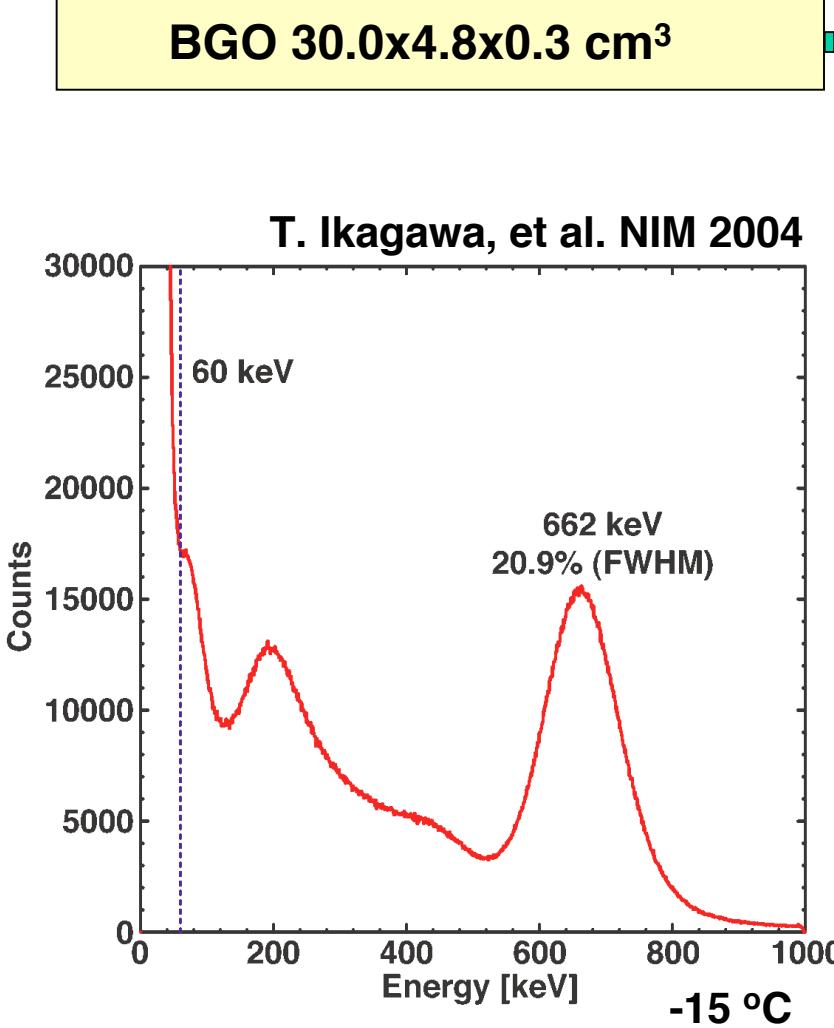
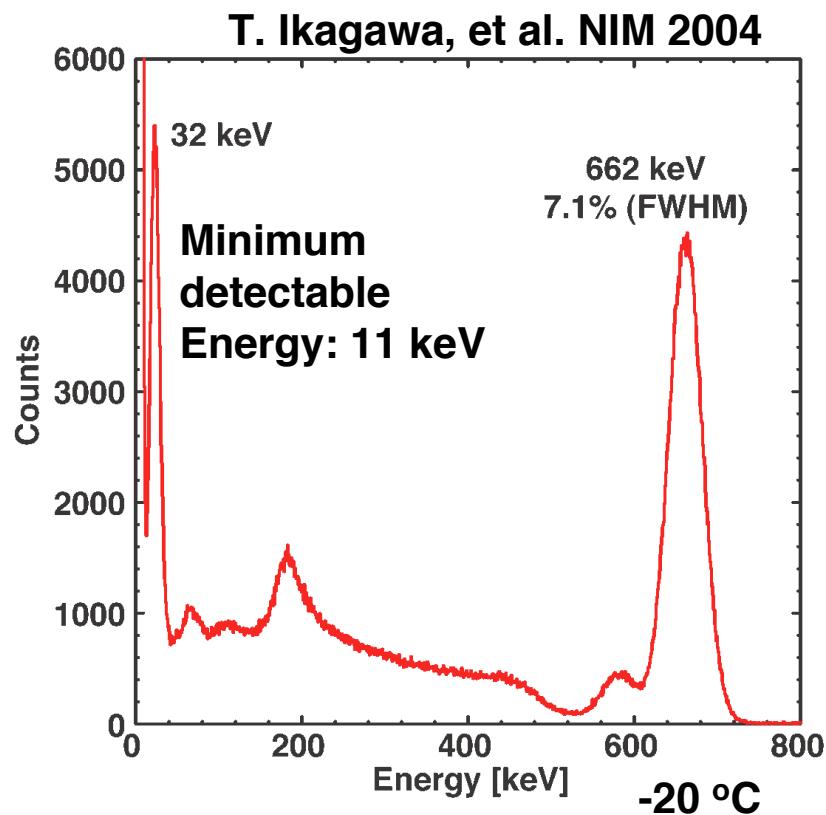


BGO Readout by APD



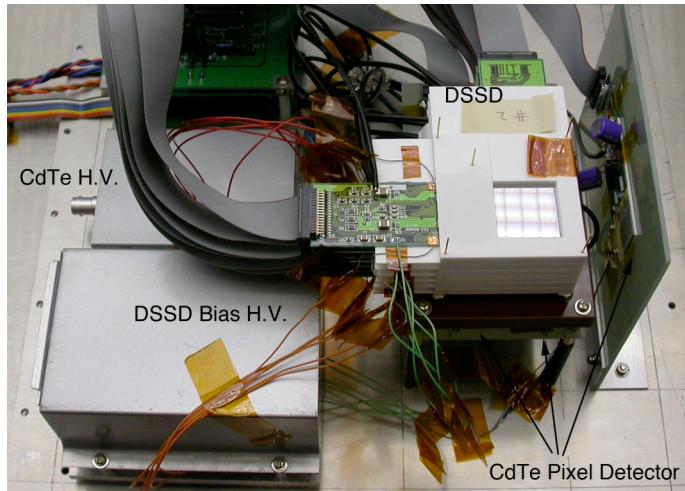
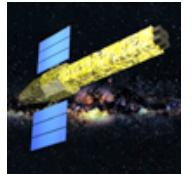
BGO
 $1.0 \times 1.0 \times 1.0 \text{ cm}^3$

HPK S8664-1010N
 $1.0 \times 1.0 \text{ cm}^2$

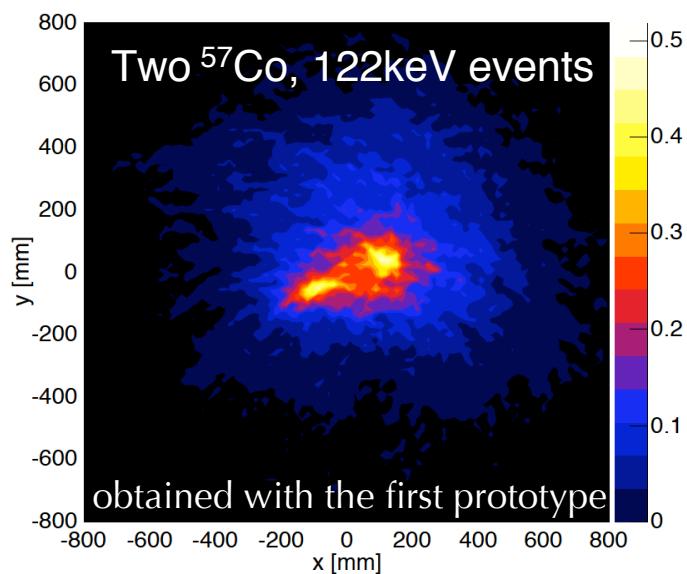




Compton Reconstruction

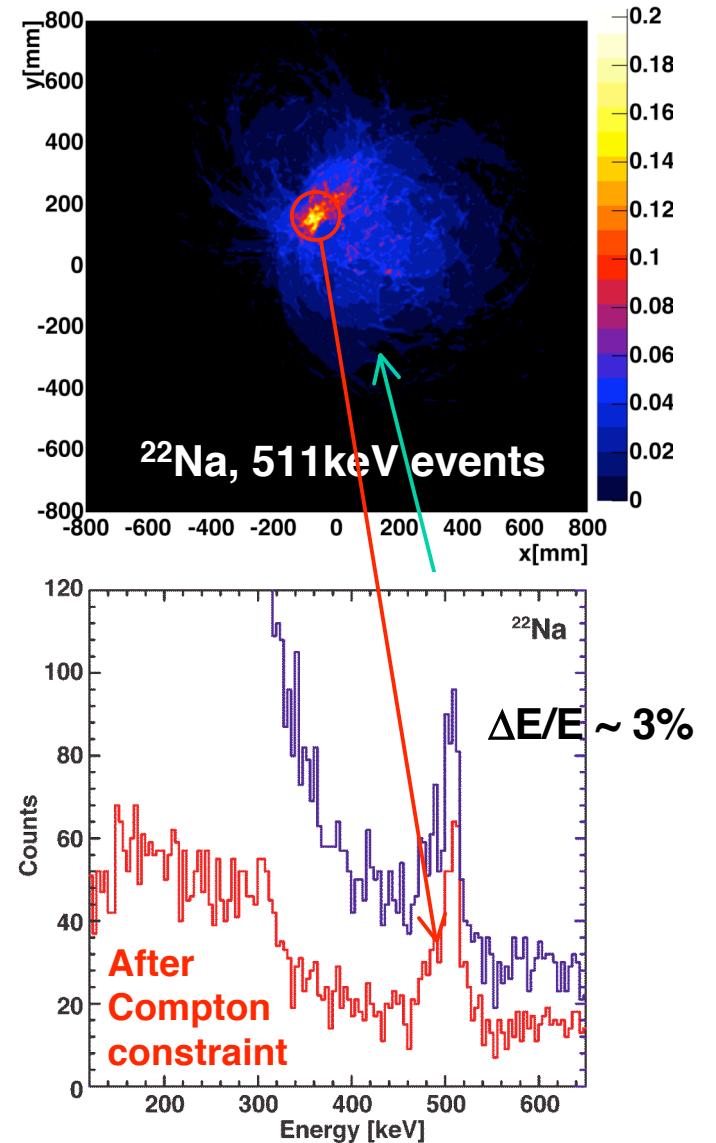


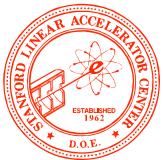
Stack of 6 DSSDs
3 CdTe detectors



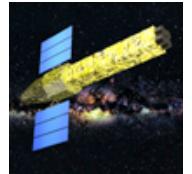
S. Watanabe, et al.
IEEE TNS 2005

Operated at $\sim -5^\circ\text{C}$

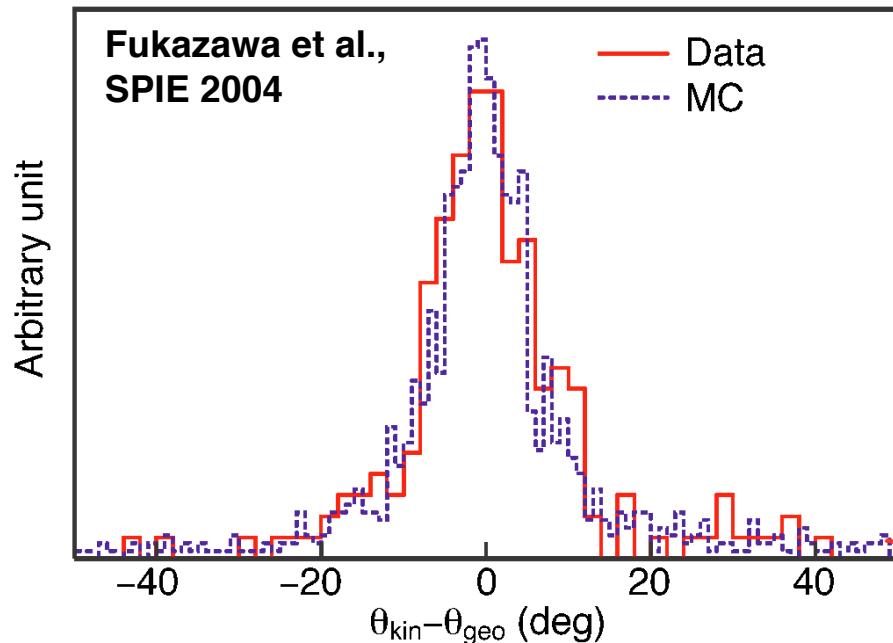




Angular Resolution

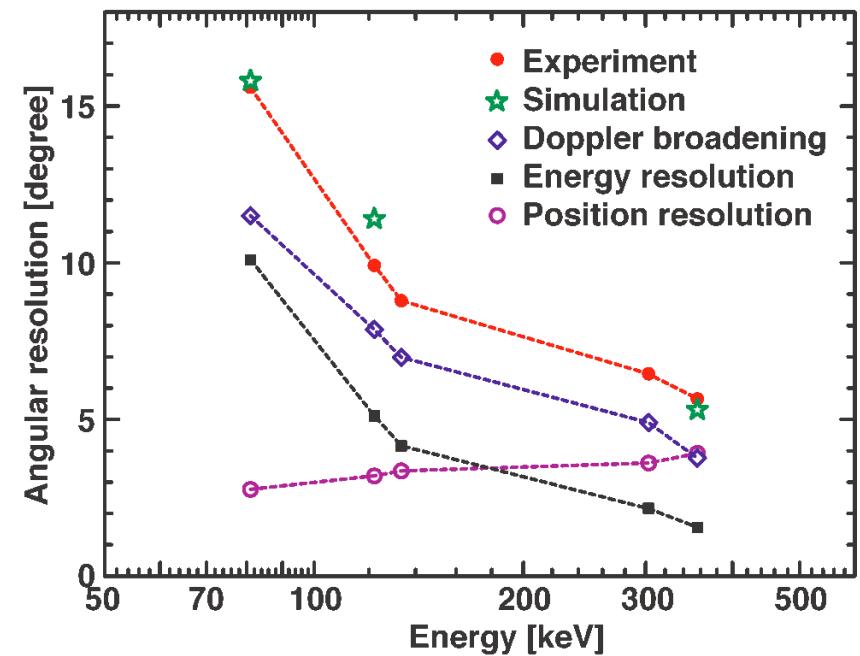


Scattering angle resolution @ 122 keV



Experimental angular resolution is dominated by Doppler broadening.

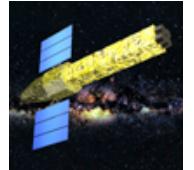
Energy dependence



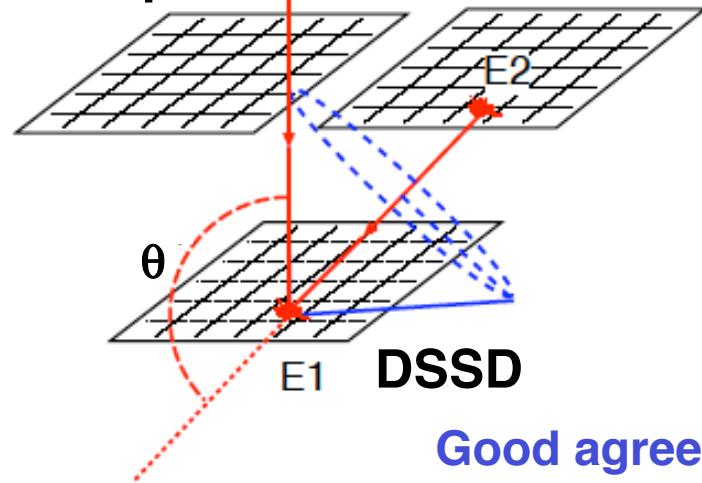
Tanaka et al., SPIE 2004



Polarization Measurement @SPring-8

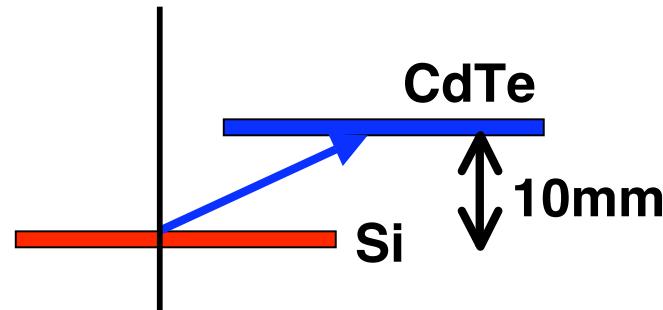


CdTe pixel detector

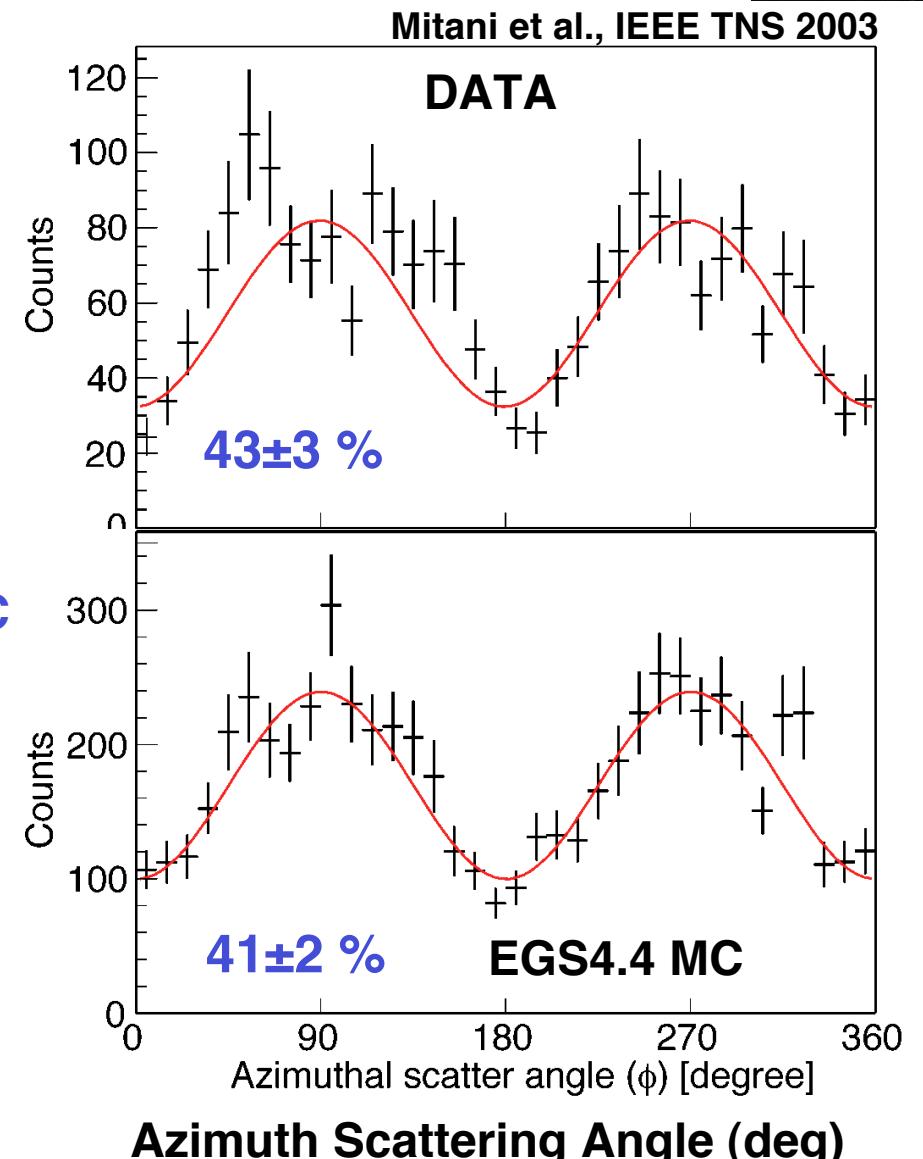


Good agreement
between data and MC

177 keV polarized photon

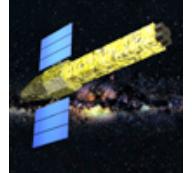


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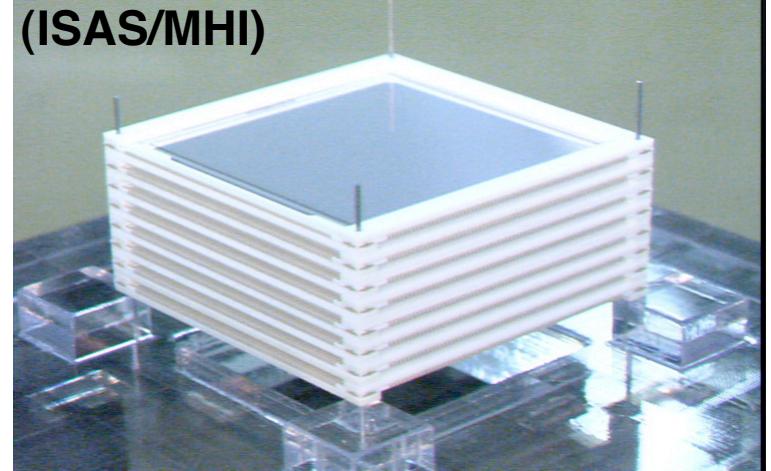


Conclusions and Future Prospects



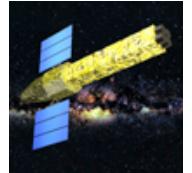
- Good energy resolution is achieved.
- CdTe technologies are getting mature.
 - Uniform CdTe properties.
 - Good bump bonding yield.
- Compton reconstruction demonstrated.
 - Angular resolution.
 - Polarization.
- R&D still required.
 - Compact packaging.
 - Thick CdTe detectors.
- Imaging polarization mission.
 - HEFT mirrors.

4x4 cm² DSSD stack
with readout electrode on the side

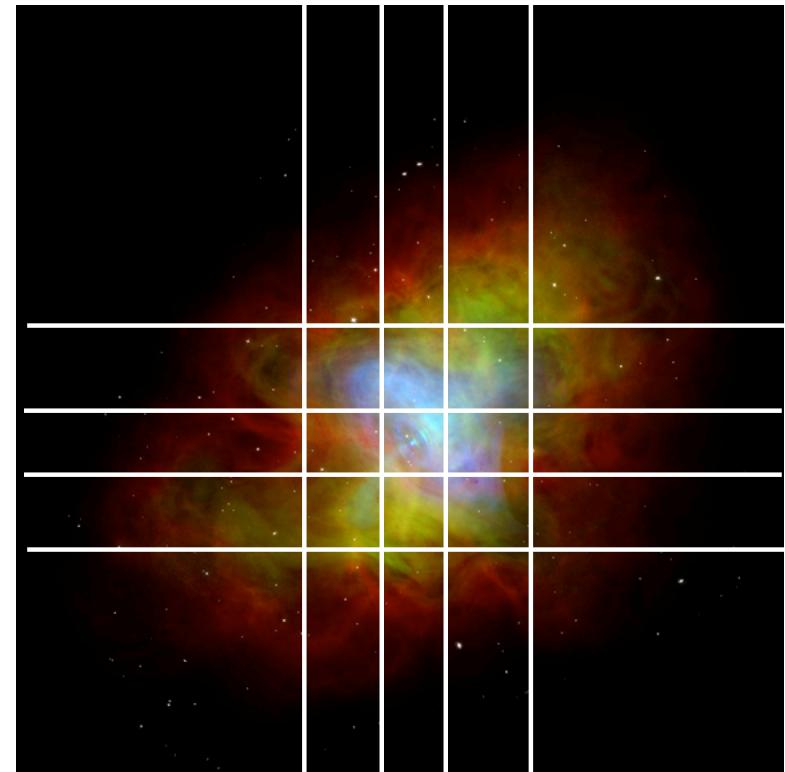
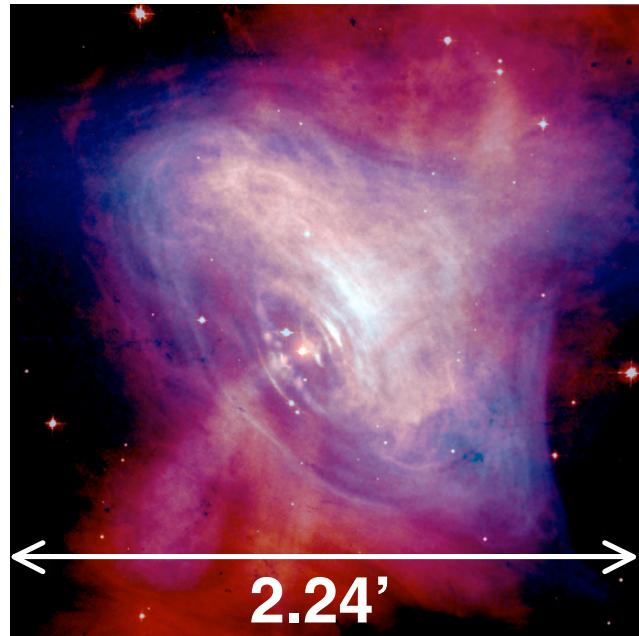




HEFT-SCT Imaging Polarimeter



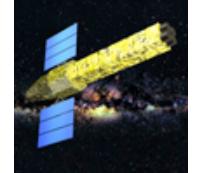
- HEFT mirror and SCT (Semiconductor Compton Telescope) combination.
 - Map polarization of Crab nebula in a balloon flight.



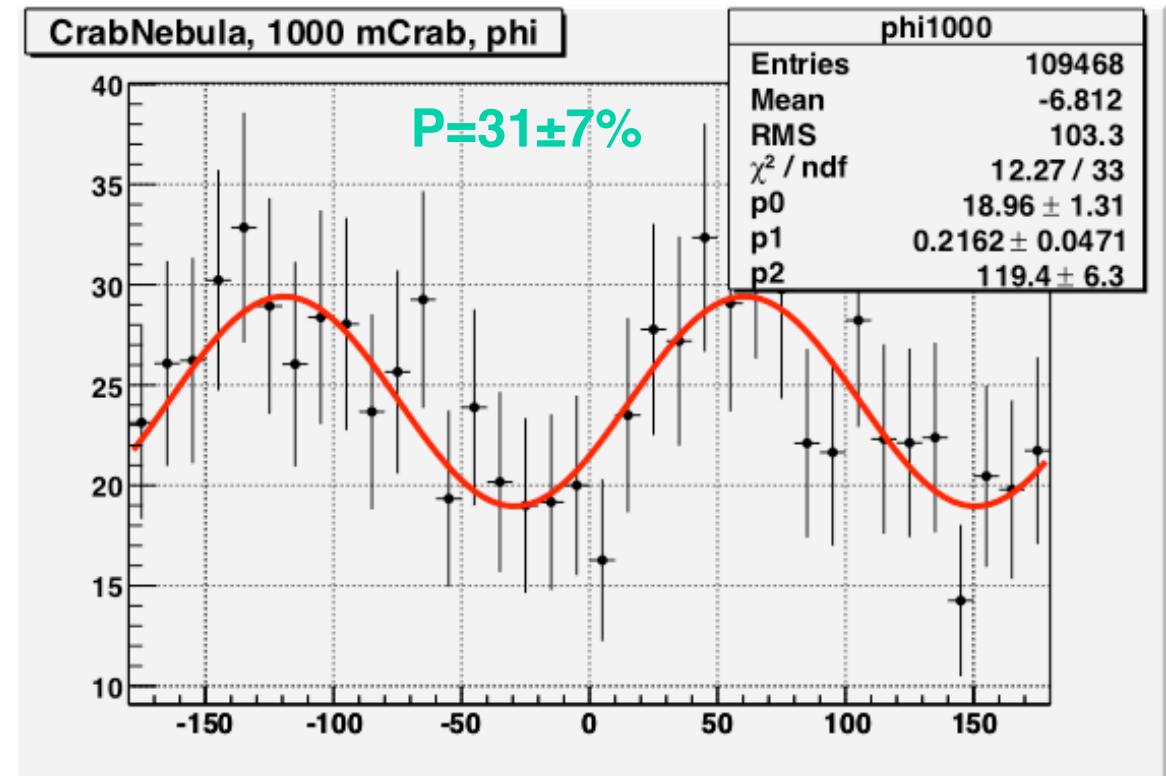
Development of Semiconductor Compton Telescope,
H. Tajima, LLNL seminar, OCT 18, 2005

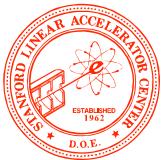


Crab Nebula Polarization Sensitivity

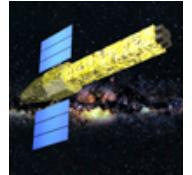


- **Sensitivity for Crab nebula polarization. ($P=19.2\%$)**
 - **12 DSSD layers, 1 Mirror configuration.**
 - 3σ measurement in 20 ks observation.
 - 32-layer configuration improves the sensitivity by a factor of 1.4.

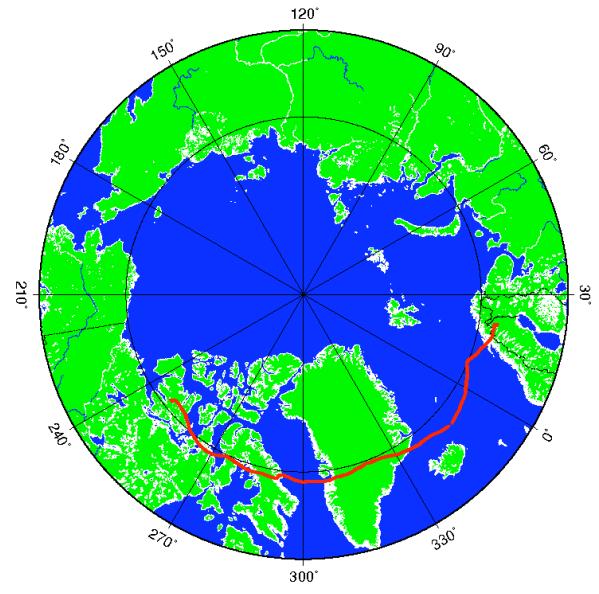




Ultimate Goal



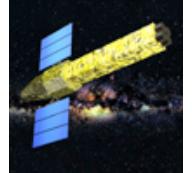
- **Polarization map of Crab Nebula**
 - **Requires a factor of >20 more photons.**
 - 32-layer configuration: factor ~ 2 .
 - Multiple mirror/detector configuration: factor ~ 3 .
 - Long duration flight (Sweden – Canada)
 - 5 days X 0.5 duty cycle = 200 ks: factor ~ 10 .



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NeXT Mission Road Map



- **2004/Jan: ISAS science committee selected NeXT over VSOP-2 for next science mission. (Engineering committee selected Solar sail.)**
- **2004/Aug: ISAS/JAXA decided not to make decision on next mission.**
- **2005/Mar: ISAS/JAXA calls for next mission proposals. (NeXT, VSOP-2, Solar sail will likely be accepted for prephase-A study.)**
- **2005/Sep: Submission of final mission proposals.**
- **2006/Jan: Selection of the next mission.**
- **2006/Apr: Phase-A study.**
- **2007/Apr: Start Proto-model fabrication.**